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Research Article

GROUNDWATER FLOW MODELING IN CHITWAN DUN VALLEY (BETWEEN NARAYANI RIVER AND LOTHAR KHOLA), NEPAL

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ABSTRACT

Models are simplification of reality to investigate certain phenomena or to predict future behavior and always tries to generate scenario that is close to the real condition. Groundwater flow models are computer models generated through using established flow equations that simulate and predict aquifer conditions. The result of groundwater modeling is used for groundwater management and remediation. In the present study, hydrostratigraphic units were identified through interpreting the lithological logs of the drilled wells then fence diagram was prepared with three major aquifer horizons, namely unconfined, shallow confined and deep confined aquifers. In addition, hydrogeologic data were integrated to develop a conceptual hydrogeologic model of the aquifer system of the Chitwan Dun valley, which was the basis for the development of the numerical model. The aquifer system was modeled numerically using MODFLOW-2005 numerical modeling, which was further calibrated and an acceptable numerical model was obtained which showed different flow direction in each aquifer layer. The model was validated by comparing the observed and simulated heads. The result shows that in each of the aquifer layers, the general flow direction is towards west and south-west.

Keywords: Groundwater flow, Hydrostratigraphic unit, Conceptual model, Simulated head, Model validation

INTRODUCTION

Fresh water is essential component of all forms of life, which is mainly obtained from surface water and groundwater (McMurry & Fay, 2004). Groundwater represents the subsurface fresh water that occurs beneath the water table in the saturated permeable geological formations. Groundwater is one of the key natural resources of the world as it plays a vital role in ensuring livelihood security across the world and can provide a uniquely reliable source of high-quality water for human uses (WWAP, 2009). Densely populated cities, small towns and villages in the world heavily depend on groundwater for water supplies since surface water has potential to be polluted by human activities and it is inadequate in some places. The fundamental importance of groundwater is that it meets the water demand of rapidly expanding urban, industrial and agricultural sectors where surface waters are scarce and seasonal. Likewise, the uneven distribution of surface water resources and requirement of significant investment has emphasized on development of groundwater resources that is available almost right below the place of demand. However, in order to properly access the resource and to minimize the negative impact to the resources due to exploitation, development of numerical model is preferable approach for its sustainability.

Groundwater modeling is an important tool to provide guidance for management of groundwater particularly in the areas where the hydrological cycles are predicted to be accelerated due to climate change (Mall *et al.*, 2006). Groundwater systems have been studied by the use of computer based mathematical models (Brassington, 2017). A mathematical model is aimed to simulate groundwater flow using the governing equation to represent the actual physical processes occurring in the natural system. In addition, the heads along the flow boundaries of the model are assigned to produce simulated heads.

Thus, a mathematical model describes the physical processes and boundaries of a groundwater system (assigned by the modeler) using governing equations. A numerical model divides space and/or time into discrete pieces and the features of the governing equations and boundary conditions (e.g. aquifer geometry, hydrogeological properties, pumping rates or sources of solute) can be specified as varying over space and time (Kumar, 2015). As discussed by Scanlon *et al.* (2003), numerical groundwater models are one of the best predictive tools available for managing water resources in aquifers. In the present study, groundwater flow modeling has been carried out in Chitwan Dun valley lying in the central Nepal. The model area is bounded between Narayani River in the west, Lothar Khola in the east and Rapti River in the south and Siwalik foothills in north (Fig. 1). The objective of the present study was to develop a conceptual model and carry out groundwater flow modeling in the study area.

Geological setting of the study area

The Chitwan Dun valley is one of the largest Dun valleys in the Himalayan foothills of Nepal. The Dun valleys are one of the ten natural divisions in Nepal Himalayas

(Hagen, 1969). These tectonic Dun Valleys are considered to be part of the Siwalik. The Siwalik region extends continuously as the southern mountain range of the Himalayas. The Chitwan Dun valley is a NNW-SSE trending valley, about 140 km long and 60 km wide, formed within the Sub-Himalayas (Siwaliks) of Nepal Himalayas, which is surrounded by sedimentary rocks (sandstone, mudstone and conglomerate) of Neogene period encircling the valley. It is low-lying land in the central part of the valley, which consists of sand, silt, and gravel (Dangol & Poudel, 2004, Tamrakar *et al.*, 2008). The Dun valley in the Siwaliks represents the active front of the Himalayan chain and represents tectonic or structural depression in the post Siwalik time. These are the youngest formations of the Himalayas and extend in a strike direction parallel to the Himalayas (Haffner, 1979). The Bhabar zone area in the Chitwan district is estimated 280 km^2 (Sharma, 1995) while the area of the Dun valley estimated as 800 km^2. The Chitwan Dun lies at a slightly higher elevation than the Terai plain.

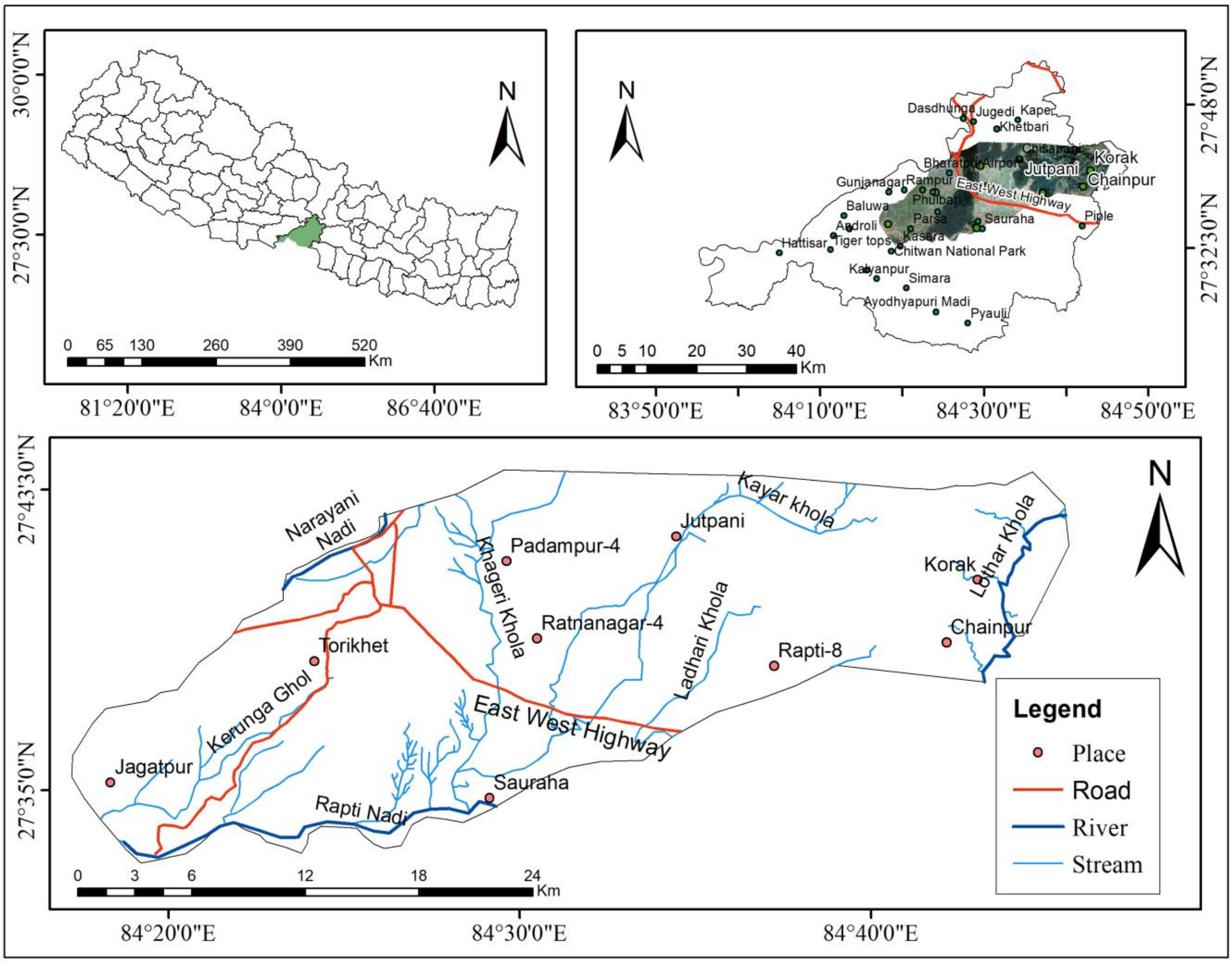

Fig. 1. Location map of the study area in Chitwan district

The study area covers the unconsolidated sediments ranging in size from clay to boulder. The southern part of the study area borders the Rapti River and Siwalik Range, attaining to heights of up to 800 m. The Rapti valley steadily widens from east to west. The eastern valley floor is covered by the broad alluvial fans of tributaries emerging from the Mahabharat Range. In the west, the floor of the basin consists of alluvial deposits of the Narayani River (Haffner, 1979). Bashyal (1998), and Neupane and Shrestha (2009) described that the Churia group rocks are faulted, folded and thrusted to the south over the recent alluvium. The geology of the western part of the study area comprises of Narayani Alluvium which consists of swamp, levee and riverbed sediments; Narayanghat Sand that consists of fine to coarse sand; Bharatpur Sand which consists of unsorted sediments boulder/cobble, pebble; and Devghat Gravel that consists of gravel, boulder/cobbles/pebbles (Morris *et al.*, 2003).

METHODOLOGY

Groundwater recharge

Empirical relationship developed by Kumar and Seethapathi (2002) has been used to estimate groundwater recharge. The relationship between rainfall and recharge is given in equation (1).

$$R = 0.63\,(P - 15.28)^{0.76} \quad (1)$$

Where, R = recharge (mm/year) and P = precipitation (mm)

The rainfall data recorded at Rampur meteorological station has been used to calculate the recharge.

Groundwater flow modeling

In this study, different materials and methods were employed to achieve the objectives. The available hydrogeologic data from the study area were collected, mainly lithologs and hydrogeological parameters. Among them thirty four well logs were used to prepare fence diagram showing different hydrostratigraphic units, with one unconfined and two confined aquifer horizons. Different parameters were used to assist with developing a conceptual model for groundwater flow. In general, the knowledge on topography, sub-surface geology, hydrogeology, land form, climate, surface soil, groundwater level and water use condition serves as an important parameters on groundwater flow modeling. The methodology followed the standard procedures adopted from Anderson and Woessner (1992), starting with the hydrogeologic model conceptualization. Preparation of conceptual model involves demarcation of the model area, deciding appropriate boundary conditions, and creation of three dimensional model of hydrogeological system. A model represents a simplified form of the real world aquifer system and assists with understanding and managing a groundwater resource (Bear *et al.*, 1992). The nature of the conceptual model determines the dimension of the numerical model and the design of the grid. Failures of numerical models to make accurate predictions can often be attributed to errors in the conceptual model (Kahsay, 2008).

In the present study, while developing conceptual groundwater flow model GIS has been extensively used for creation of database and spatial distribution of the groundwater recharge has been calculated with the simple empirical recharge estimation methods. After constructing the conceptual model, the software MODFLOW had been selected as the computer code, which is the modular three dimensional finite difference groundwater model developed by United States Geological Survey (McDonald & Harbaugh, 1988; Harbaugh & McDonald, 1996). Subsequently, conceptual model so developed can be converted into a mathematical model that simulates groundwater flow indirectly by means of a governing equation thought to represent the physical processes that occur in the system, together with equations that describe heads or flows along the boundaries of the model (Pathak, 2015). For the groundwater flow modeling, the conceptual model had been prepared for the aquifer system, which includes the delineation of aquifer layers in the area, rivers and boundary conditions.

In most of the groundwater problems, the water density was considered to be constant and hence it can be excluded in the mathematical derivation (Hantush, 1964). Groundwater flow in homogeneous isotropic media was expressed by partial differential equation using the principle of mass conservation and momentum conservation (Trescot & Larson, 1977). Darcy's velocity can be applied for such media and the three-dimensional movement of ground water of constant density can be described by the 2nd order tension (Dimou & Bacassis, 1993) of hydraulic conductivity as expressed below in equation (2).

$$\partial/\partial x(K_{xx}\,\partial h/\partial x)+\partial/\partial y(K_{yy}\,\partial h/\partial y)+\partial/\partial z(K_{zz}\,\partial h/\partial z)+W=S_s\,\partial h/\partial t \quad (2)$$

Where,

- K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity (L/T)
- h is the potentiometric head (L)
- W is a volumetric flux per unit volume representing sources and/or sinks of water, with W<0.0 for flow out of the ground-water system, and W>0.0 for flow into the system (T^{-1})
- S_S is the specific storage of the porous material (L^{-1}); and t is time (T)

The modeling process consisted of developing a conceptual model, selecting numerical model, and calibrating the model to observed values, verifying calibrated model and modifying model. The information necessary for the flow modeling are hydrostratigraphic units, hydraulic heads, fluxes in streams, boundary conditions, hydraulic conductivity, and recharge. The MODFLOW software in the Visual MODFLOW Flex interface developed by Waterloo Hydrogeologic Inc. was used for three dimensional groundwater flow modeling. The advantage of MODFLOW is that it provides different modules to undertake 3-D groundwater flow simulations in confined and unconfined aquifers as well as in aquifers with variable confinement with both constant and variable transmissivity values (Hernandez-Carrera & Gaskin, 2006). The simulation features of MODFLOW have been extensively tested and its theory is well documented;

besides it is relatively easy to understand and apply to real conditions (Leake, 1997).

RESULTS AND DISCUSSION

General

Groundwater is the basic source of water for people in the Chitwan Dun valley, which is one of the largest Dun valleys in the Himalayan foothills of Nepal. The geological structure of the region consists of old and new alluvium, both of which constitute alluvial deposits of mainly sand, clay, silt, gravel and coarse fragments. The new alluvium is renewed every year by fresh deposits brought down by active streams, which engage themselves in fluvial action. Elevations range from 180 m to 263 m above sea level in the study area. Land use map of the study area was prepared from the digital topographic map of Department of Survey, Government of Nepal, which is based on the 1:50,000 scale aerial photography of 1992. The map shows that area covered by forest is 47 % and about 41% of area is covered by agricultural land. In order to calculate recharge in the study area, the precipitation data recorded at Rampur meteorological station between the period 2014 and 2018 was used, which showed the average annual precipitation of 1730.66 mm. The groundwater recharge in the study area was calculated as 180.90 mm/year from the empirical relationship developed by Kumar and Seethapathi (2002).

Hydrostratigraphic units

A hydrostratigraphic unit can be defined as a part of a body of rock/soil that forms a distinct hydrologic unit with respect to the flow of ground water (Maxey, 1964). In a review of the concept, Seaber (1988) redefined the term as "a body of rock/soil distinguished and characterized by its porosity and permeability". Delineation of these units subdivides the geologic framework into relatively more or less permeable portions and thus aids in definition of the flow system.

The complex geological formations were simplified into three aquifers and two aquitard layers which were later used in groundwater modeling. These aquifers are named as unconfined aquifer (Aquifer 1), shallow confined aquifer (Aquifer 2) and deep confined aquifer (Aquifer 3). The unconfined aquifer consists of discontinuous top soil, sand, silt and clay lenses with gravel. The aquifer thickness ranges from 58 to 116 m, the eastern part of the study area is represented by thickest layer of unconfined aquifer. The shallow confined aquifer consists of fine to coarse sand and fine to coarse rounded to sub-angular gravels, intercalated with clay, silt, fine sand and boulder. The aquifer thickness ranges from 20 m to 110 m. Thick layer of shallow confined aquifer is distributed in central and western part of the study area. Likewise, the deep confined aquifer consists of medium to coarse sand and medium to coarse rounded to angular gravel beds, intercalated with clay, silt, fine sand and boulder.

Hydrostratigraphic units comprise of geological units of similar hydrogeologic properties. Among thirty four only twenty-eight borehole were used to prepare stratigraphic cross-section which covered the study area. These boreholes were drilled for groundwater exploitation and their lithologs were helpful to demarcate aquifer and non-aquifer layers. Nine stratigraphic lithological cross- sections were taken in N-S and E-W directions thereby interpreting different layers. Fence diagram is prepared based on the stratigraphic cross-sections (Fig. 2).

A fence diagram is a graphical display of three-dimensional data and interpretations in two-dimensional perspective view and it is useful tool to observe lithological types of different selected boreholes at the same time, as it represents multiple logs in a single diagram. The contour map for bottom of three aquifer layers with respect to mean sea level (msl) was prepared, which was used as input data during groundwater flow modeling.

Hydraulic Parameter

Hydraulic conductivity (K) is an important parameter in relation to the flow of groundwater through an aquifer system. It is defined as the capacity of a porous medium to transmit water (Driscoll, 1986). As field aquifer testing was outside the proposed scope of work for the study, actual pump test data was unavailable for the calculation of aquifer parameters. Where relevant data was available, the calculation of aquifer parameters was based on the following assumptions:

* Transmissivity (T): Where the maximum yield of the borehole was available, transmissivity values were either derived from a literature source or calculated on the basis of a qualified guess where T (m^2/d) = 10*Q. ‘Q’ represents discharge and is measured in l/s (Van Tonder *et al.*, 2002).
* Hydraulic conductivity (K): In the absence of pump test data, hydraulic conductivity, porosity, storativity and specific yield values were derived from literature sources where actual borehole testing was undertaken.
* In case, the pumping test was absent in some wells, the generalized values of hydrogeologic parameters have been used.

The rate of groundwater movement is governed by the hydraulic conductivity of an aquifer and the hydraulic gradient (Todd, 1980). Among thirty four boreholes, fourteen boreholes penetrated only the unconfined aquifer layer, twenty boreholes reached up to the shallow confined aquifer and six boreholes penetrated the deep confined aquifer layers. The screened zones in each well site and the hydraulic conductivity values for respective aquifer zones were taken into consideration in order to interpolate the aquifer horizons between the wells. Hydraulic properties of borehole data helped in construction of different initial and boundary condition for model domain.

The stratigraphic cross-section and water level in each aquifer shows that water flows towards south in North to South section (Fig. 3). While in case of east-west section the water level in aquifers is controlled by the Lothar Khola in the east and Narayani River in the west Stratigraphic cross sections also show that the aquifer thickness is more in northern part that is towards Siwalik foothills compared to the southern part of the study area.

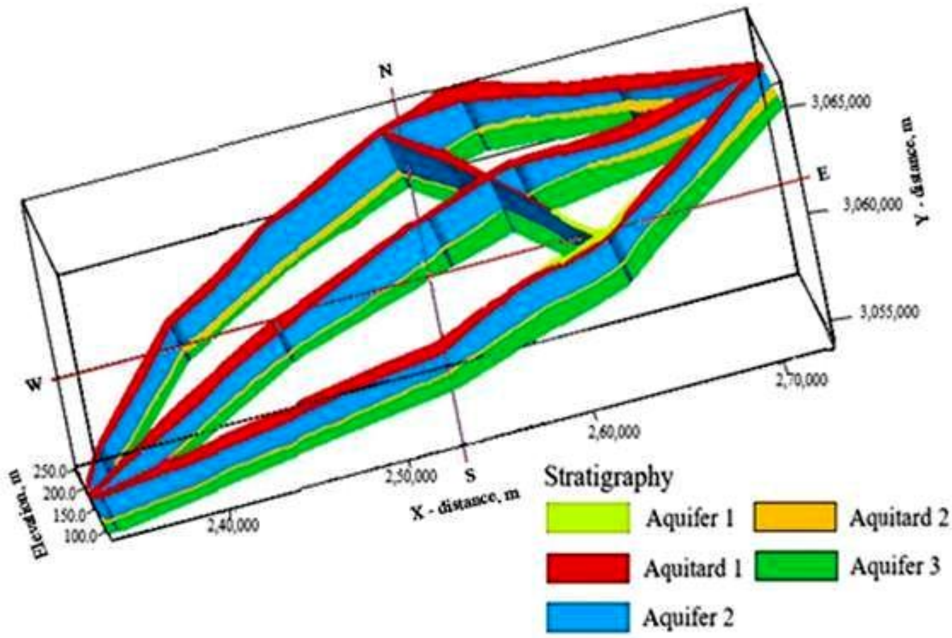

Fig. 2. Fence diagram of the study area showing different aquifer layers

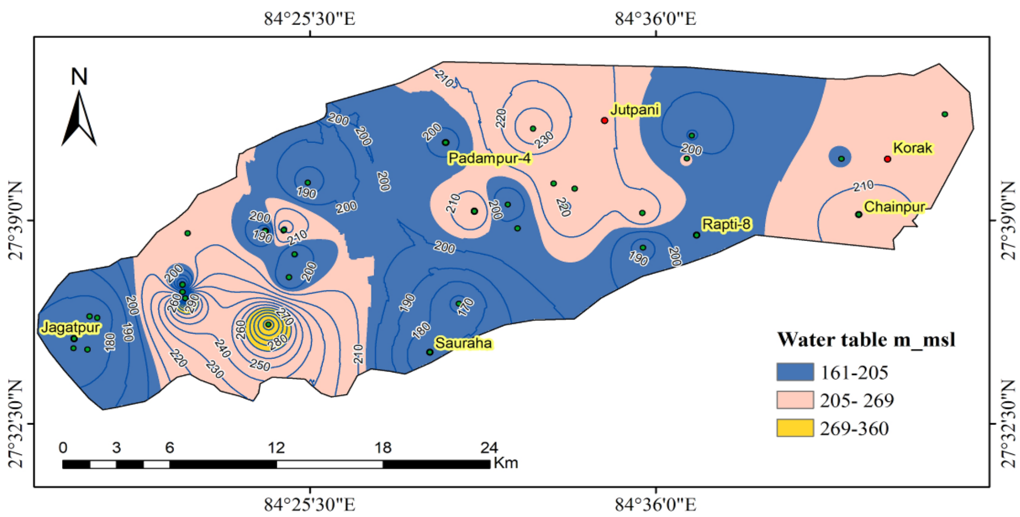

Fig. 3. Water table (m, asl) map of the study area

Conceptual model

In order to solve any site-specific hydrogeological problem, it is necessary to collect, compile and analyze related primary and secondary data and articulate the important aspects of the hydrogeological system of the site, which is known as a conceptual model (Kresic & Mikszewski, 2013). The conceptual model incorporates the known information about the hydrogeological system and then provides a framework to design the numerical model. The conceptual model of the study area has been developed by integrating the available data on hydrogeology, well logs, geological map, and hydrostratigraphic units. The model domain is bounded by three rivers in west, south and east, therefore river boundary conditions are applied along these parts of the model domain. In the northern boundary of the model area, there lies the Siwalik foothill. The general head condition was assigned along the northern part of the model domain. River condition simulates the water flow between aquifer and superficial water on the model cells for which this condition was selected. If the head in the aquifer is above the head in the river, water will flow from the aquifer to the river. If the opposite occurs, water will then flow from the river to the aquifer. The cells within the model domain are active and outside the model domain are inactive (Fig. 4).

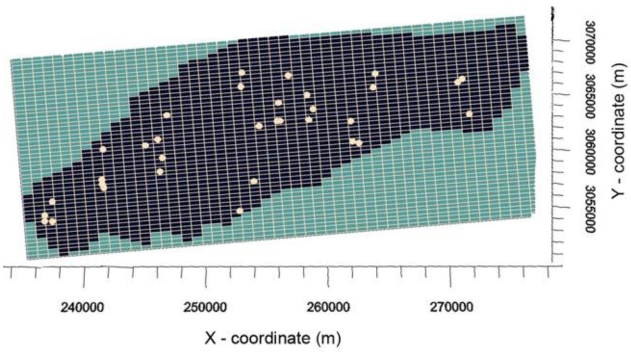

Fig. 4. Model domain showing active (black) and inactive (grey) cell with well points

The initial condition in numerical groundwater model is the initial head distributions, which is important to achieve the convergence criteria of the numerical scheme. The model convergence issue appears when the computer codes fail in their calculation by numeric instabilities due to large hydraulic gradient between heads of boundary elements and non-boundary elements. Therefore, the initial heads of the model should be only in the range with the values of the hydraulic head condition at the boundary element of the model to achieve the steady state condition.

Model calibration

Model calibration is an important part of the groundwater modeling, which is required to ensure that the model can successfully simulate observed aquifer behavior. The hydrogeological parameters like recharge and hydraulic conductivity are systematically altered during the calibration process till the computed values matches observed values within an acceptable level of accuracy (defined by root mean square error). Guidelines for effective model calibration using automatic parameter identification (nonlinear regression) have been proposed by Hill and Tiedeman (2007).

In the present study, the hydraulic heads obtained from groundwater level measurement data were used as calibration values. Calibration was conducted through trial and error by varying aquifer hydraulic parameters and comparing calculated heads to those measured in boreholes. During the calibration, hydraulic conductivities of three layers were modified manually and trial runs were carried out. From the output of the each run, different error parameters such as correlation coefficient, residual mean, standard error of estimate and normalized root mean squared error were determined and the error quantifying analysis was done.

Universal inverse modeling code (UCODE), an inverse parameter estimation application (Poeter & Hill, 1998) was used to estimate the model parameters. During each stages of adjustment of some parameter values, the computed and observed heads were compared. A final model was developed that has the observed and computed heads very close, with the standard error of estimate as 0.234 m; residual mean as 1.45 m; normalized root mean square error (RMSE) as 5.65 % and correlation coefficient as 0.89 at the calibrated values. The comparison between observed and simulated heads is shown in Fig. 5.

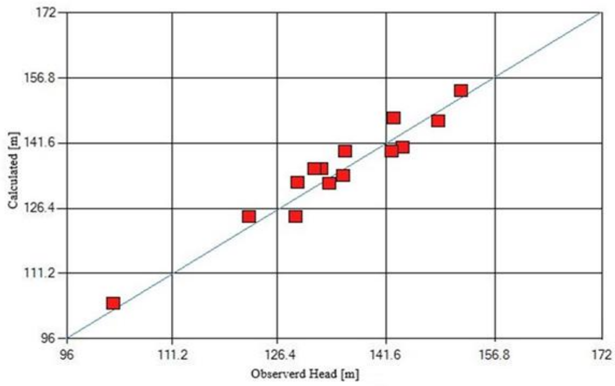

Fig. 5. Comparison between observed and computed heads

The groundwater flow model

The hydraulic head values for each cells in the model domain is the main output from the model. A water table surface can be interpolated from these hydraulic head values in meter above mean sea level (m amsl). The water table is shown as contour lines representing an interpolated surface that indicates the hydraulic head of the model domain. The location of the water table reflects the interaction between surface water and groundwater. The model shows the groundwater flow in different aquifer horizons within the study area. Simulated hydraulic head of unconfined aquifer shows that the hydraulic head ranges from 214 m to 140 m above mean sea level (Fig. 6). The value of simulated head decreases towards the south-west part of study area. This is due to the fact that both the west and south part of the study area. The unconfined aquifers are recharged through the rivers in these locations. The shallow confined aquifer shows the decreasing value of simulated hydraulic head towards south western part of the study area (Fig. 7).

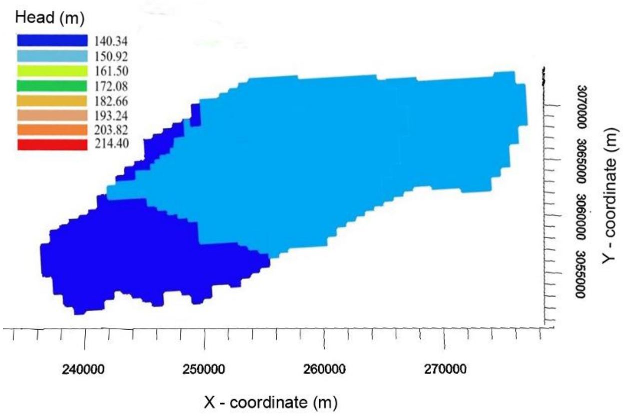

Fig. 6. Simulated hydraulic head (m amsl) in unconfined aquifer layer

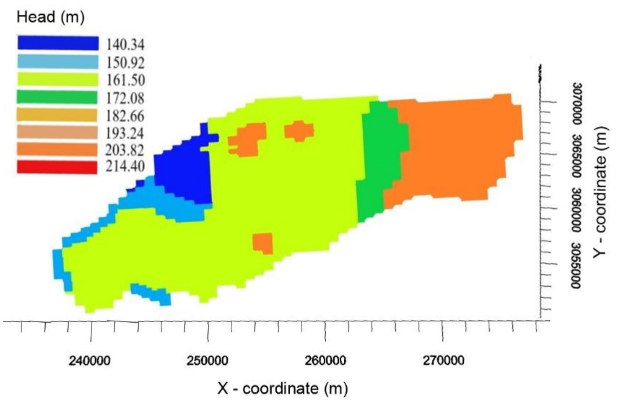

Fig. 7. Simulated hydraulic head (m amsl) in shallow confined aquifer layer

The third aquifer layer (deep confined aquifer) shows that simulated hydraulic head ranges from 214 m to 140 m (Fig. 8). The simulated hydraulic head in this aquifer layer decreases from east part towards the southern and western part of study area.

The simulated hydraulic heads for all aquifers was in good accordance to the field condition, i.e. water moves into the natural drainage that is towards Narayani River in the west and Rapti River in the south in all the aquifers. The unconfined aquifers are principally recharged either through the rivers flowing through the model boundary or through the Siwalik foothill. The Siwalik foothill being at higher elevation and the river valleys being at lower elevation, the general groundwater flow is from north to south or south west. The simulated heads also reflects this situation, which is in agreement with that of the field condition.

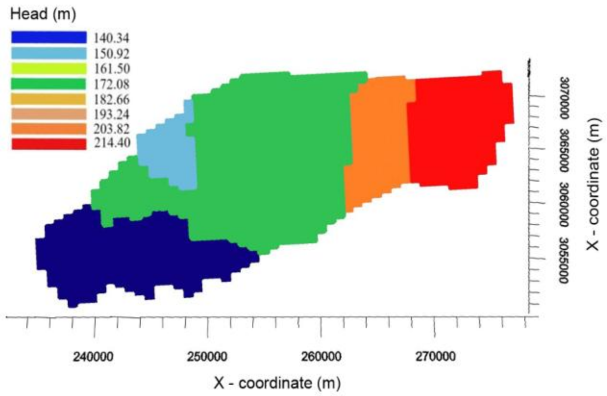

Fig. 8. Simulated hydraulic head (m amsl) in the deep confined aquifer layer

CONCLUSION

The aim of this study was to develop a model for the groundwater system for Chitwan Dun valley aquifer system where groundwater is the main source of fresh water. All the available data regarding physiography, meteorology, geology and hydrogeology of the system have been collected, evaluated and utilized to develop a conceptual model for the system. The data from 34 boreholes were selected in the study leading to prepare groundwater flow model. Five different hydrostratigraphic units have been delineated from the lithologs of wells among which three layers are aquifers and two layers are aquitards. The three aquifer layers were distinguished as unconfined aquifer, shallow confined aquifer and deep confined aquifer.

The conceptual model represents for the depth of around 127 m and three units are identified based on borehole data which are unconfined aquifer at the top, shallow confined aquifer, and deep confined aquifers and these three units were used in numerical model for calibration. Different cross-section from north to south as well as west to east direction and the direction profile of the model shows that water moves into the natural drainage that is towards Narayani River in the west and Rapti River in the south in all the aquifers. The numerical model shows higher hydraulic heads in northern part that decreases towards the south in the study area. The cross section of model layer in east-west showed that the values of head decreased towards Narayani and Rapti River which clearly showing the influence of rivers.

The recharge in the study area calculated by the empirical method is found to be 180.9066 mm/year whereas discharge is 26 mm/year which is very low comparative to recharge this show that study area has very high potential for groundwater. Sufficient amount of extraction is possible without significant effect to the aquifer system.

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